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THE TRANSMISSION OF NEUTRONS AND GAMMA-RAYS THROUGH AIR SLOTS. PART IV. THE EFFECT OF AN OFFSET ON THE TRANSMISSION OF NEUTRONS THROUGH AN AIR SLOT IN WATER

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September 1, 1954

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THE TRANSMISSION OF NEUTRONS AND GAMMA-RAYS THROUGH AIR SLOTS

Part IV

The Effect of an Offset on the Transmission of Neutrons Through an Air Slot in Water

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1 September 1954

REACTOR DEPARTMENT

BROOKHAVEN NATIONAL LABORATORY
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Part IV

The Effect of an Offset on the Transmission of Neutrons Through an Air Slot in Water

As an aid in shielding against the passage of neutrons in air slots, the expedient often employed is to put a step or offset in the slot to impede the direct travel of radiation. As part of our investigation of neutron transmission through slots we studied the effect of a single such offset for slots of thickness 0.5 and 1.5 inches with an overall length of 48 inches. Both sections of the slot were 24 inches long by 34 inches wide and the offset distance, D, was varied from zero to a few inches. This variation was small compared with the 40-inch source plate, so that the source remained effectively infinite in size. Fig. 1 is a sketch indicating the essentials of the experiment. An infinite offset was accomplished approximately by having the bottom section filled with water. An experiment, to be discussed later, included a horizontal gap connecting the two vertical air slots.

Thermal neutron data were taken in the water above the upper slot with both fission and BF_3 counters. The usual procedure was to make a vertical traverse along the upper slot centerline. For small values of offset, when the transmission was large, the fission counter was employed. For larger offsets, the 1 x 6 inch BF_3 counter was used. Horizontal traverses were also taken in the thickness direction at vertical positions corresponding to about 1.5 and 7.5 inch water separations between the top of the aluminum box and the detection center of the counter. The vertical traverses for the 0.5 inch thick slot are presented in the semilog plot of Fig. 2. Ordinates are thermal flux per unit pile power and abcissae represent the height of the detector above the bottom of the water tank. The top of the slot holder assembly was at Z = 52.5 inches. Nomenclature appearing in the figure is described in Part I of this series of reports.

Qualitative features of the traverses which bear comment are the following:

For large Z, the 1/e length is approximately 7 cm; characteristic of fast neutrons.

For small Z; i.e., 54 inches, the 1/e length varies with offset and is larger for smaller offset. The behavior is consistent with the assumption that with large offsets the emergent spectrum of neutrons is softer than with small offsets.

The peaks of horizontal traverses made in the neighborhood of Z = 54 inches have been normalized to the flux measured in the vertical traverses at 54 inches. The assumption is made that the shapes of horizontal traverses taken with Z differing by fractions of an inch are closely the same. These normalized data are presented in Fig. 3.

From the peak flux measured at 54 inches, using different values of offset, D, one obtains curve A given in Fig. 4. Curve B results from peak fluxes corresponding to Z = 60 inches. The characteristic to note is

the slow decrease followed successively, as the offset is increased, by a rapid decrease, and then a slow decrease. Shown at the right hand side are fluxes obtained with the bottom slot filled with lucite; i.e., an infinite offset. For large offset curve B is much flatter than curve A. This is interpreted to mean that the higher energy component which is detected at the larger water separation of curve B is better collimated and that the interaction effect is smaller.

A question of interest is whether the features observed for the 0.5 inch thick slots are the same for slots of different thickness. Data were obtained with 1.5 inch thick slots which allowed comparison with the 0.5 inch data. Figs. 5 and 6 show vertical and horizontal traverses obtained when the upper half of the 1.5 inch thick slot was displaced. In Fig. 7, corresponding to Fig. 4, the qualitative behavior for the 1.5 inch thick gap is observed to be the same as with the 0.5 inch gap.

The similarity of shape for the two thicknesses is demonstrated in Fig. 8. Ordinates for the 1.5 inch points were determined by dividing the flux by the square of the ratio of slot thicknesses; i.e., a factor of 3^2, or ninefold. Abcissae are in slot thickness units; i.e., offset divided by slot thickness. It is seen that the lower curve shape is essentially independent of slot thickness, whereas the upper curve, which included softer radiation, after transformation is not independent of slot thickness. It appears that for the more energetic neutrons, as a first approximation, the offset shape is independent of slot thickness.

For displacements from zero to one slot unit, it is reasonable to assume that, as a first approximation, the transmitted flux will be due to unscattered neutrons. The response function can then be calculated over this range of displacements if one assumes that the problem is two dimensional and that the detector integrates the emergent flux. This calculation, for those neutrons which do not penetrate water, is done in appendix A, and yields a $T^2 - D^2$ dependence, where T is the slot thickness and D is the slot offset. In Fig. 9, curve B of Fig. 8 is replotted and a calculated curve is shown for which the flux is normalized at D = 0, and decreases with D according to $T^2 - D^2$.

It is apparent, however, that when D approaches T substantial contributions to the transmitted flux must come from neutrons which have traversed some water in the region of the offset. In appendix B are outlined calculations which estimate the contribution coming through the corners. For this purpose, it is assumed that fast neutrons are attenuated with a 1/e length in water of 2.0 inches. The calculation for D/T greater than unity was made at only two points; D = 1.625 and 2.0 inches for T = 1.5 inches. A summary of these calculations will be found in Table I in appendix B. It is seen that the simple assumption of line-of-sight behavior, including exponential attenuation in the water medium at the corners, fits the data fairly well up to D/T = 1.1. This suggests that the first approximation theory is good so long as the offset is not much larger than the slot thickness. For larger separations, one may conjecture that the interacting neutrons are not all removed from the beam, and that some of them reach the detector. This would make the experimental points lie higher than the calculated ones, particularly for D greater than T.

The difference between the experimental value and the sum of the infinite offset result and the calculated value would then represent the "inscattered" component: at D/T = 1.33 something like 8 x 10^{-3} of that obtained at zero offset.

The effect of a horizontal connecting air gap on the transmission of a stepped slot is indicated in Fig. 10. Curve B is run No. 1828 reported in Fig. 2 for the 0.5 inch thick slot with 1.8 inch offset. Curve A was obtained with the same setup, except that there was a 3 inch high connecting air space at the offset. It is seen that with the air space an increase in flux is noted, and that curves A and B are almost parallel. At Z = 54 inches, the increase is a factor of 1.48 and at 60 inches it is 1.39. If the process of transmission at the offset involved a twofold large angle scattering, the low energy neutrons from the lower slot would scatter through the horizontal section with greater probability than the high energy neutrons because the cross sections are larger for the smaller energies. This would imply that curve A would initially be steeper than curve B. There is no evidence for this. In terms of curve B in Fig. 4, the effect of the air gap was to reduce the offset from 1.8 inches to about 1.2 inches. It is fair to state that for an offset a few times the slot thickness, inclusion of a horizontal connecting gap affects the neutron transmission of the slot in a minor way.

APPENDIX A

In order to approximate the flux transmitted through offset slots, let us assume that we have a two dimensional problem, that the detector integrates the emergent flux, and that we are dealing with only neutrons which travel straight line paths between source and detector. The calculation then can be broken into two parts depending upon whether the neutron path is entirely in air or whether it also includes some water. In part A, we consider that the complete path is in air, and in part B, include the effect of water on the assumption of exponential attenuation in the water.

For a source point lying at x, one approach is to calculate the angle subtended at x, Fig. 11, by that part of the top of the slot which is defined by the corners halfway up and at the top. The assumption is made that the emergent flux is proportional to the angle subtended. The desired result is then obtained by integrating over x. For offsets, D, less than or equal to half the slot thickness, T, the desired function is:

Fig. 11

$$I_0 = \int_0^D dx\left[\operatorname{arcot}\left(\frac{D-x}{L}\right) - \operatorname{arcot}\left(\frac{D+T-x}{2L}\right)\right] + \int_D^{T-D} dx\left[\frac{\pi}{2} + \arctan\left(\frac{x-D}{2L}\right) - \operatorname{arcot}\left(\frac{D+T-x}{2L}\right)\right]$$

$$+ \int_{T-D}^{T} dx\left[\frac{\pi}{2} + \arctan\left(\frac{x-D}{2L}\right) - \operatorname{arcot}\left(\frac{T-x}{L}\right)\right] \qquad (1)$$

For D greater than or equal to T/2, and less than 1, the function is:

$$I_0' = \int_0^{T-D} dx \left[\operatorname{arcot}\left(\frac{D-x}{L}\right) - \operatorname{arcot}\left(\frac{D+T-x}{2L}\right) \right] + \int_{T-D}^{D} dx \left[\operatorname{arcot}\left(\frac{D-x}{L}\right) - \operatorname{arcot}\left(\frac{T-x}{L}\right) \right]$$

$$+ \int_D^T dx \left[\frac{\pi}{2} + \arctan\left(\frac{x-D}{2L}\right) - \operatorname{arcot}\left(\frac{T-x}{L}\right) \right] \qquad (2)$$

In all cases, the angles are very small since L = 24 inches, T = 1.5 inches. We can replace the arcot and arctan functions by the first term in their series expansions and obtain to a good approximation:

$$I_0 \simeq \int_0^D \frac{T-D+x}{2L}\, dx + \int_D^{T-D} \frac{T}{2L}\, dx + \int_{T-D}^{T} \frac{2T-D-x}{2L}\, dx = \frac{T^2-D^2}{2L} \qquad (3)$$

$$I_0' \simeq \int_0^{T-D} \frac{T-D+x}{2L}\, dx + \int_{T-D}^{D} \frac{T-D}{L}\, dx + \int_D^T \frac{2T-D-x}{2L}\, dx = \frac{T^2-D^2}{2L} \qquad (4)$$

Equations 3 and 4 can be written directly on the assumption that the angles involved are given by the chord divided by the radius, rather than the arc by radius.

APPENDIX B*

For those cases in which neutrons traverse water along part of the straight line path from the source to the top of the air slot, it is not always possible to get an algebraic expression to describe the process. We shall consider four cases:

a. D less than T;
b. D greater than T, neutrons do not traverse either of ends R or S;
c. D greater than T, neutrons traverse end R; and,
d. D greater than T, neutrons traverse end S.

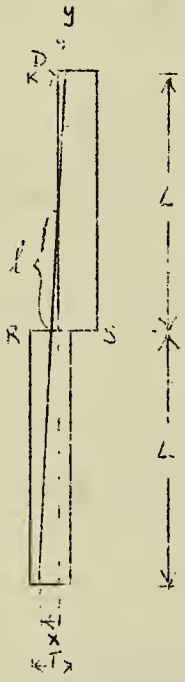


Fig. 12

Case a: For the experiments under discussion, the fast neutrons are attenuated in the water with a 1/e length of approximately 1/u = 2 inches**. Since the length L = 24 inches, then uL ≫ 1, and for significant contributions l ≪ L. From the geometry shown in Fig. 12, we can write

$$\frac{\ell}{\frac{1}{2}x-y} \simeq \frac{L+\ell}{x} \qquad \text{or}$$

$$\ell \simeq \frac{L+\ell}{2}\left(\frac{x-y}{x}\right) \simeq \frac{L}{2}\,\frac{x-y}{x}$$

The contribution to the flux at y due to a source element dx is proportional to exp (-ul). The contribution emergent through the slot top for rays passing through R is proportional to the angle dy/2L, hence:

$$I_a' = \int_0^D dx \int_0^x \frac{dy}{2L} e^{-u} \simeq \frac{1}{2L}\int_0^D dx \int_0^x dy\, e^{-\frac{uL}{2}\left(\frac{x-y}{x}\right)} = \frac{1}{2L} e^{-\frac{uL}{2}} \int_0^D dx \int_0^x dy\, e^{\frac{ul}{2}\frac{y}{x}}$$

$$= \frac{e^{-\frac{uL}{2}}}{2L}\int_0^D dx\, \frac{2x}{uL}\left(e^{\frac{uL}{2}} - 1\right) = \frac{1}{2uL^2}\left(1 - e^{-\frac{uL}{2}}\right)D^2 \simeq \frac{1}{2u}\left(\frac{D}{L}\right)^2$$

By symmetry a similar result is obtained for rays passing through S. Therefore, the total contribution is:

$$I_a \simeq \frac{1}{u}\left(\frac{D}{L}\right)^2$$

Case b: For simplicity consider the case where $T \leq D \leq 3T/2$; i.e., in Fig. 13 $d \leq T/2$. Then the path length in water is given by $\ell = d\ 2L/(x+y+d)$, and one can write

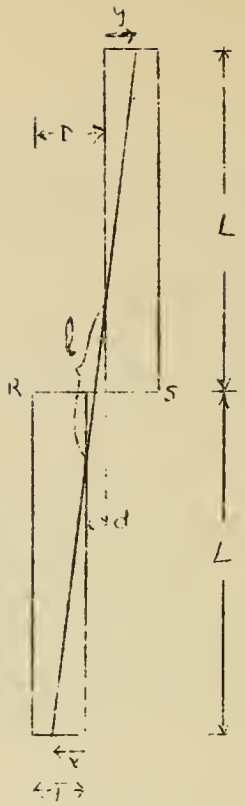


Fig. 13

$$I_b = \int_0^d dx \int_0^{x+d} \frac{dy}{2L} e^{-yL}$$

$$+\int_d^{T-d} dx \int_{x-d}^{x+d} \frac{dy}{2L} e^{-uL}$$

$$+\int_{T-d}^{T} dx \int_{x-d}^{T} \frac{dy}{2L} e^{-uL}$$

$$= \quad A \quad + \quad B \quad + \quad C.$$

Each of the integrations with respect to y is of the form

$$\int dy\, e^{-\frac{2uLd}{x+y+d}}$$

which can be expressed in terms of the exponential integrals. For example, one can substitute

$$2uLd = K; \quad x+d = a; \quad z = \frac{K}{y+a}; \quad dy = -\frac{K}{z^2}\, dz$$

Hence,

$$A = -\frac{K}{2L} \int_0^d dx \int_{\frac{K}{a}}^{\frac{K}{2a}} dz\ \frac{e^{-z}}{z^2} = -\frac{K}{2L} \int_0^d dx \left[E_2\left(\frac{K}{x+d}\right) - E_2\left(\frac{K}{2(x+d)}\right) \right]$$

Similarly the terms B and C may be expressed in terms of exponential integrals of the second order giving

$$I_b = -\frac{K}{2L} \left\{ \int_0^d dx \left[E_2\left(\frac{K}{x+d}\right) - E_2\left(\frac{K}{2(x+d)}\right) \right] + \int_d^{T-d} dx \left[E_2\left(\frac{K}{2x}\right) - E_2\left(\frac{K}{2(x+d)}\right) \right] \right.$$

$$\left. + \int_{T-d}^{T} dx \left[E_2\left(\frac{K}{2x}\right) - E_2\left(\frac{K}{T+x+d}\right) \right] \right\}$$

The integration with respect to x can be carried out graphically for particular values of d and K.

Case c: For those rays which traverse end R of Fig. 13 one has

$$\ell \simeq L \frac{x+d-y}{x+d+y}$$

$$I_c \simeq \int_d^T dx \int_0^{x-d} e^{-uL \frac{x+d-y}{x+d+y}} \frac{dy}{2L}$$

letting

$$x+d = m;\ uL = c;\ z = 2\frac{mc}{m+y};\ dy = -2mc\,\frac{dz}{z^2};\ e^{-\frac{cm-y}{m+y}} = e^{c} e^{-\frac{2mc}{m+y}}$$

$$I_c \simeq -\frac{2c}{2L} e^{c} \int_{2d}^{T+d} m\,dm \int_{2c}^{\frac{mc}{x}} \frac{e^{-z}}{z^2}\,dz = \frac{c}{L} e^{c} \int_{2d}^{T+d} m\,dm \left[E_2\left(\frac{mc}{x}\right) - E_2(2c)\right]$$

Case d: For those rays which traverse end S of Fig. 13, one has

$$\ell \simeq uL \frac{y+d-x}{y+d+x}$$

and analogous to case c, can write

$$I_d \simeq \int_d^T \frac{dy}{2L} \int_0^{y-d} dx\, e^{-uL\frac{y+d-x}{y+d+x}} = I_c$$

The following table contains a summary of computations for Fig. 9. The constants involved are: u = 0.5; T = 1.5 inches; and L = 24 inches.

TABLE I

Summary of Computations

	NORMALIZED TO UNITY AT D = 0[a]						NORMALIZED TO 1.08×10^3 AT D=0[a]
D/T	I_0	I_a	I_b	I_c	I_d	Total	Total
0	1.0	0				1.0	1.08(3)
0.5	.75	.0416				.792	8.56(2)
0.75	.438	.0936				.532	5.75(2)
0.90	.19	.135				.325	3.51(2)
1.00	0	.167				.167	1.8 (2)
1.083			$2.81^{(-2)}$	$1.47^{(-2)}$	$1.47^{(-2)}$	$5.75^{(-2)}$	6.21(1)
1.33			$3.38^{(-3)}$	$0.17^{(-3)}$	$0.17^{(-3)}$	$3.72^{(-3)}$	4.01

[a] (n) means times 10^n

* We wish to acknowledge the contribution of Bruce Knight to these calculations.

** Derived from the curves in Fig. 1 of BNL-2028, Part X of this series.

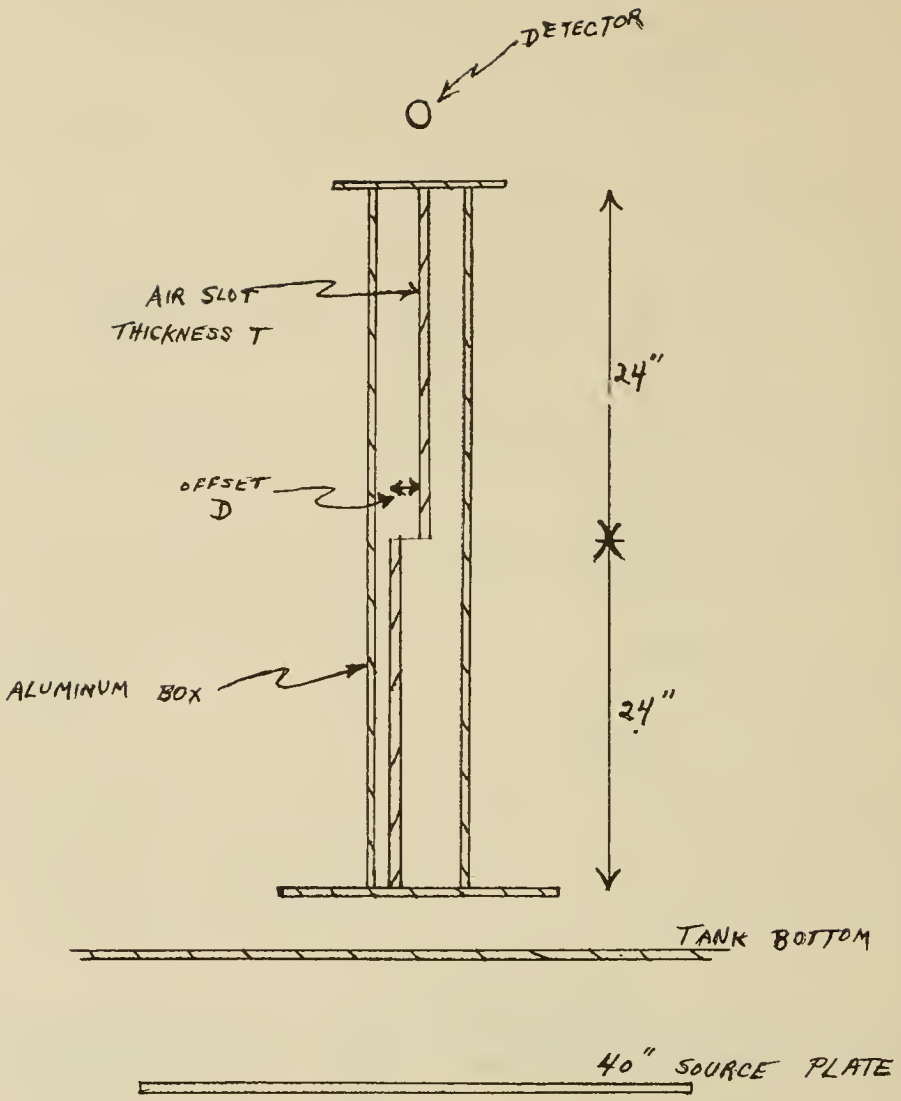


Fig. 1

SINGLE OFFSET

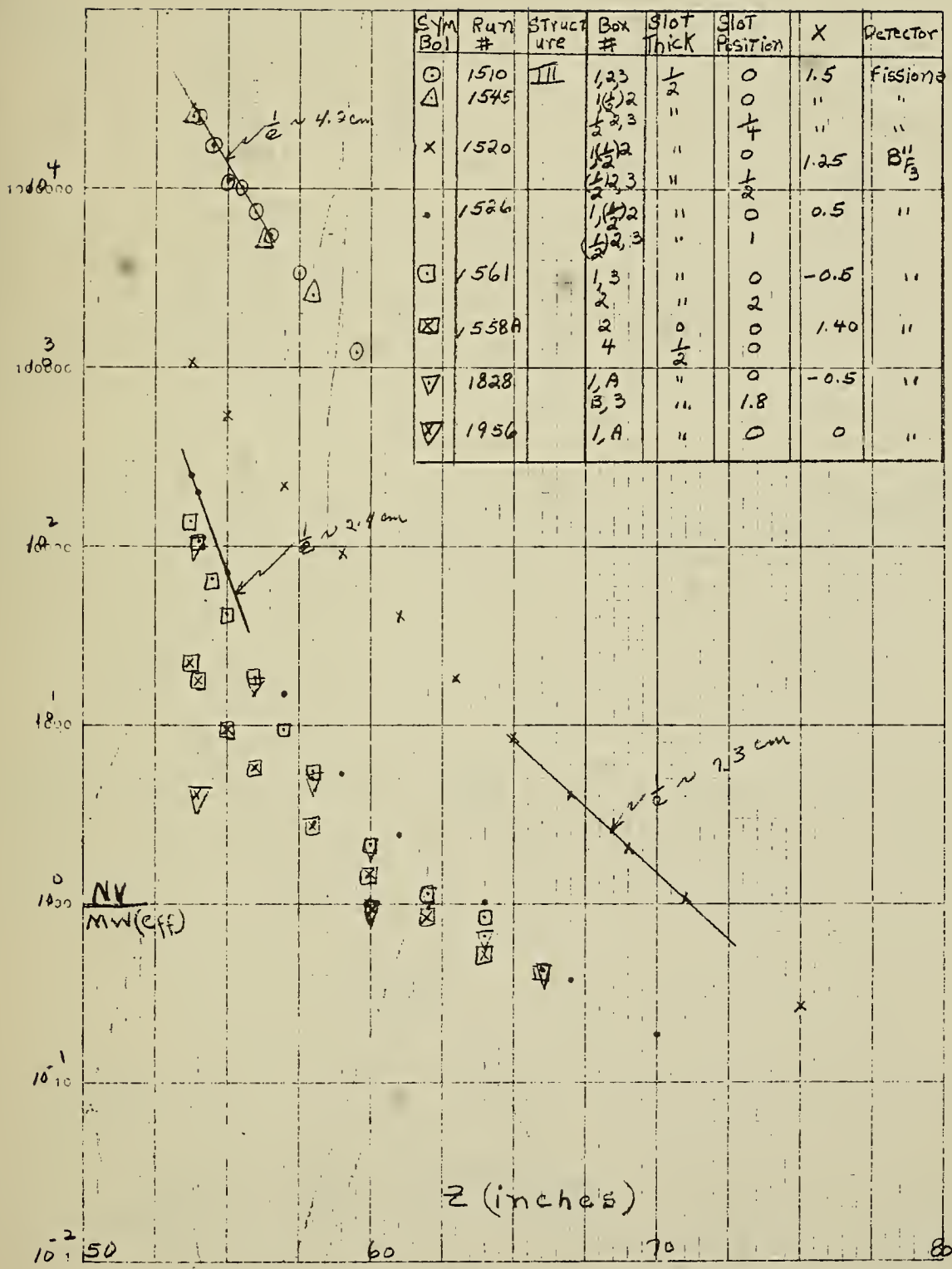
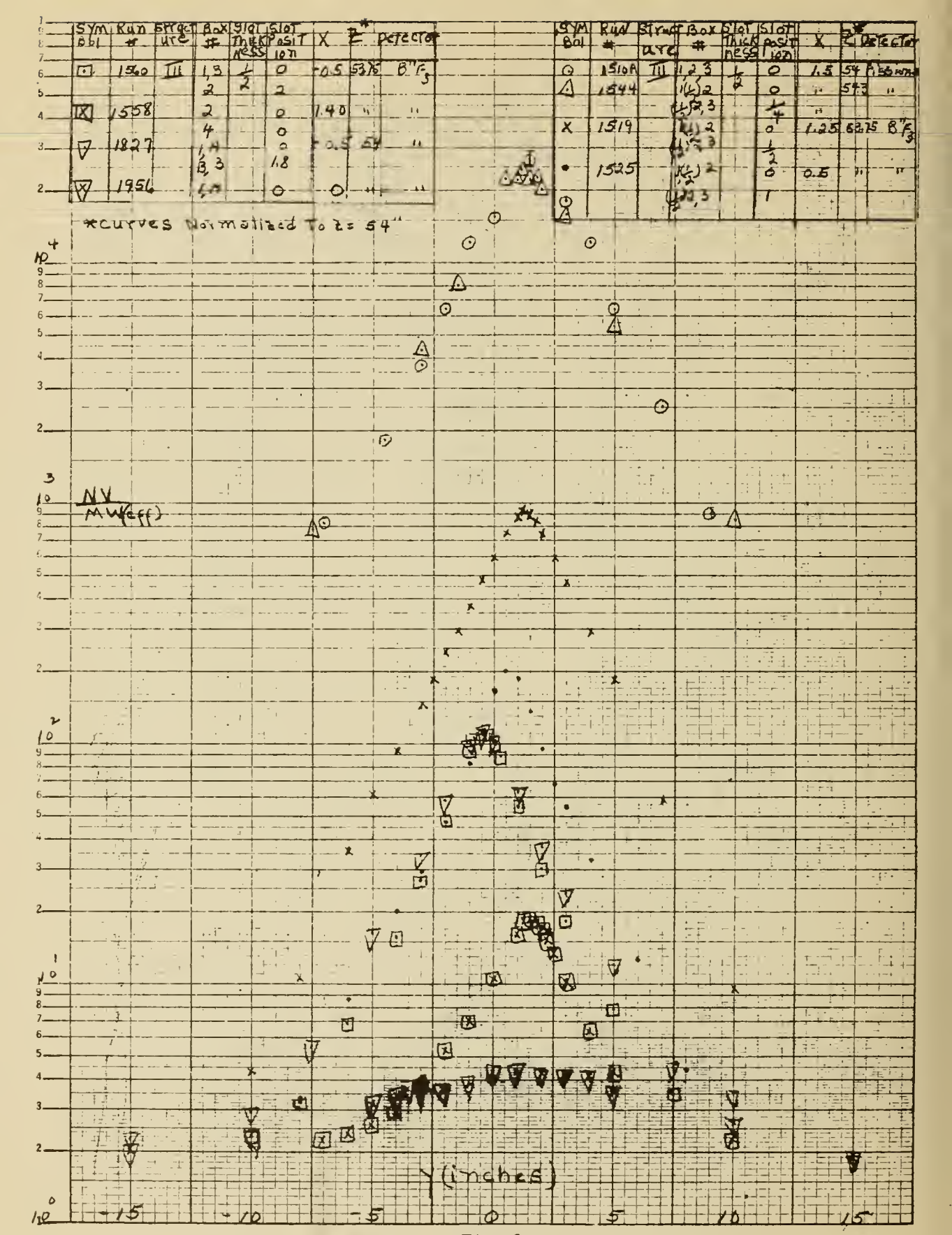

Symbol | Run # | Structure | Box # | Slot Thick | Slot Position | X | Detector
1510 | III | 1,2,3 | 1/2 | 0 | 1.5 | Fissions
1545 | 1(1/2)2 | " | 0 | " | "
1/2 2,3 | " | 1/4 | " | "
1520 | 1(1/2)2 | " | 0 | 1.25 | B11 F3
1/2 2,3 | " | 1/2 |
1526 | 1,(1/2)2 | " | 0 | 0.5 | "
(1/2)2,3 | " | 1 |
1561 | 1,3 | " | 0 | -0.5 | "
2 | " | 2 |
1558A | 2 | 0 | 0 | 1.40 | "
4 | 1/2 | 0 |
1828 | 1,A | " | 0 | -0.5 | "
B,3 | " | 1.8 |
1956 | 1,A | " | 0 | 0 | "
1/e ~ 4.3 cm
1/e ~ 2.1 cm
1/e ~ 7.3 cm
NV
MW(eff)
Z (inches)
50
60
70
80

Fig. 2



SYM Bol | Run # | Structure | Box # | Slot Thickness | Slot Position | X | Z* | Detector
1560 | III | 1,3 | 1/2 | 0 | -0.5 | 53.75 | B"F3
2 | 2
1558 | 2 | 0 | 1.40 | " | "
4 | 0
1827 | 1,4 | 0 | -0.5 | 54 | "
3,3 | 1.8
1956 | 0 | 0 | " | "
SYM Bol | Run # | Structure | Box # | Slot Thickness | Slot Position | X | Z* | Detector
1510A | III | 1,2,3 | 1/2 | 0 | 1.5 | 54 | Fission
1544 | 1(1/2)2 | 0 | " | 54.3 | "
1/4 | "
1519 | 1(1/2)2 | 0 | 1.25 | 53.75 | B"F3
1/2
1525 | 1(1/2)2 | 0 | 0.5 | " | "
1
*curves Normalized To z = 54"
NV / MW(eff)
Y (inches)
-15
-10
-5
0
5
10
15

Fig. 3

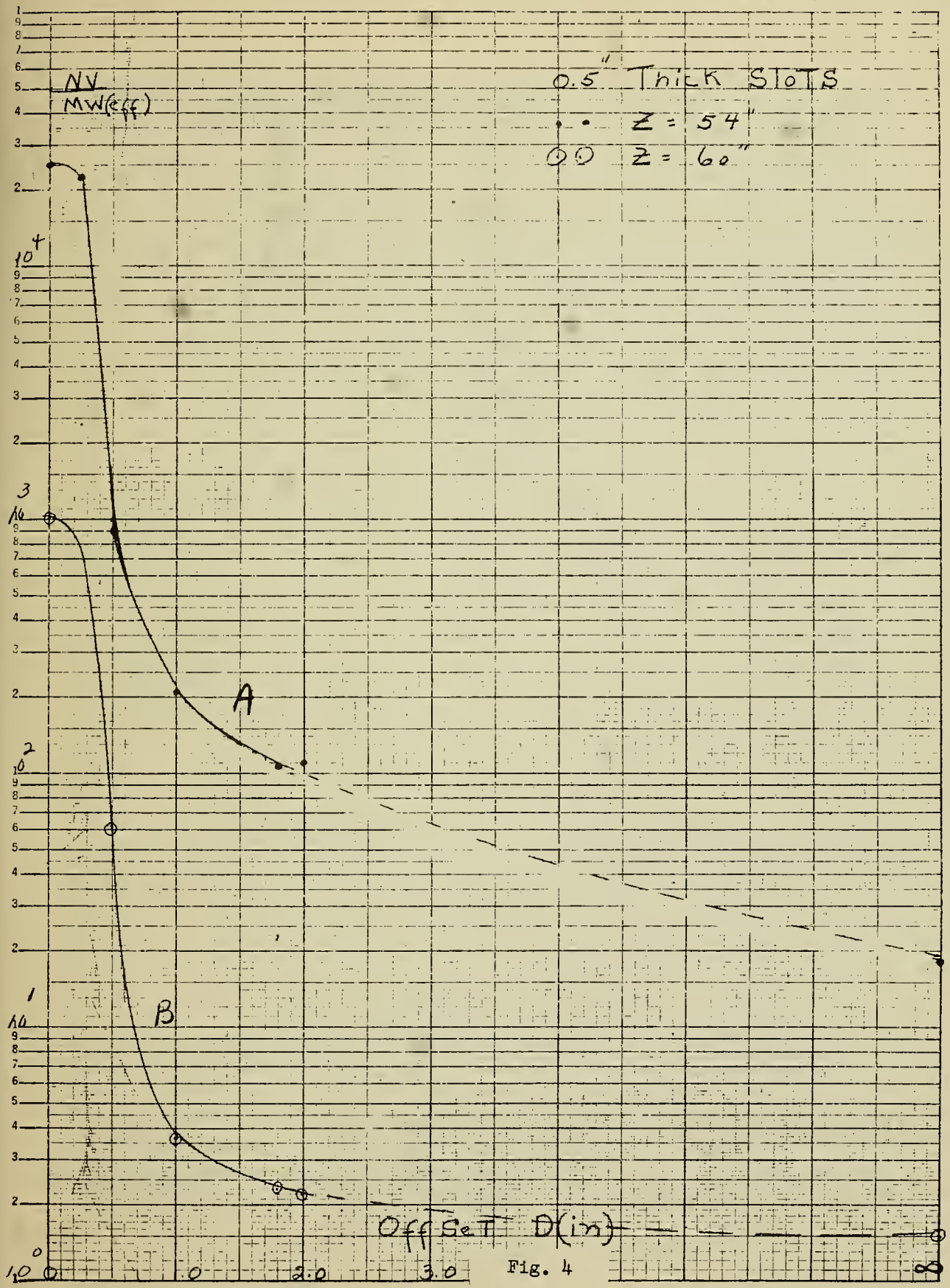


Fig. 4

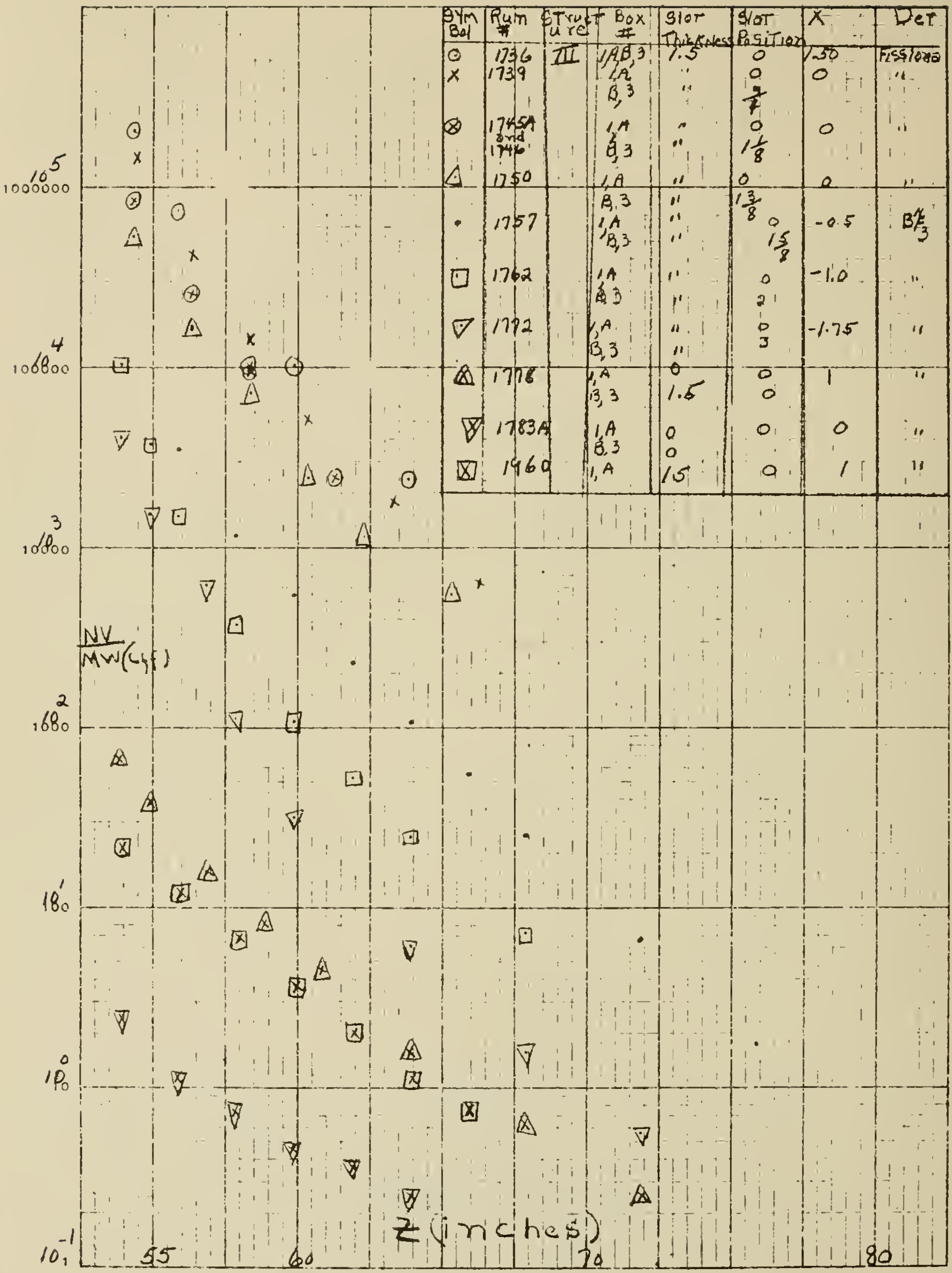
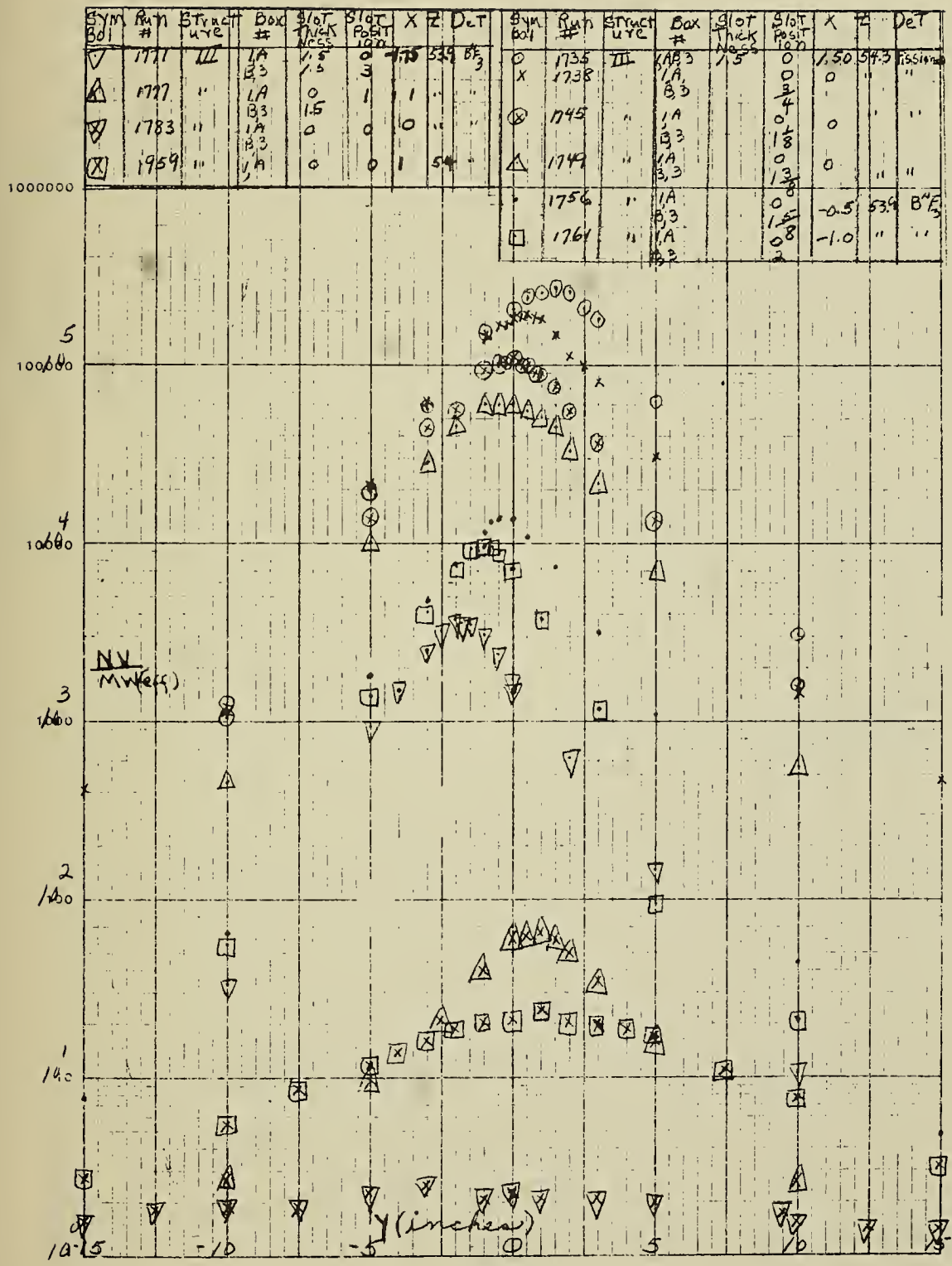

Sym Bol
Run #
Structure
Box #
Slot Thickness
Slot Position
X
Det
1736
1739
1745A and 1746
1750
1757
1762
1772
1778
1783A
1960
Fission
Z (inches)
55
60
70
80

Fig. 5



Sym Bol
Run #
Structure
Box #
Slot Thickness
Slot Position
X
Z
Det
1771
1777
1783
1959
1735
1738
1745
1749
1756
1761
1000000
5
4
3
2
1
NV
MW(eff)
Y (inches)
-10
-5
0
5
10

Fig. 6

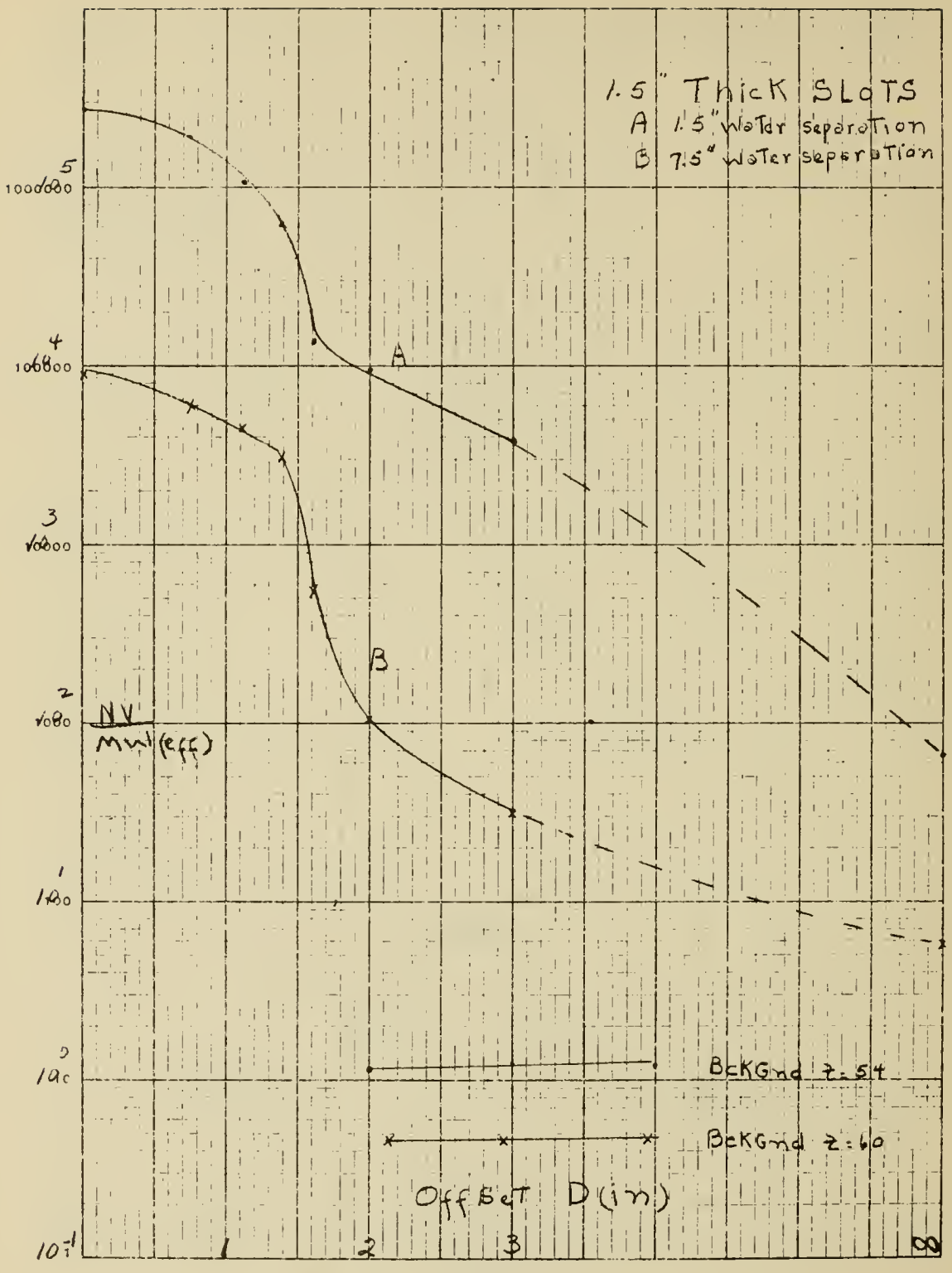

1.5" Thick SLATS
A 1.5" Water separation
B 7.5" Water separation
A
B
NV
Mw (eff)
BcKGnd 2.54
BcKGnd 2.60
Offset D (in)

Fig. 7

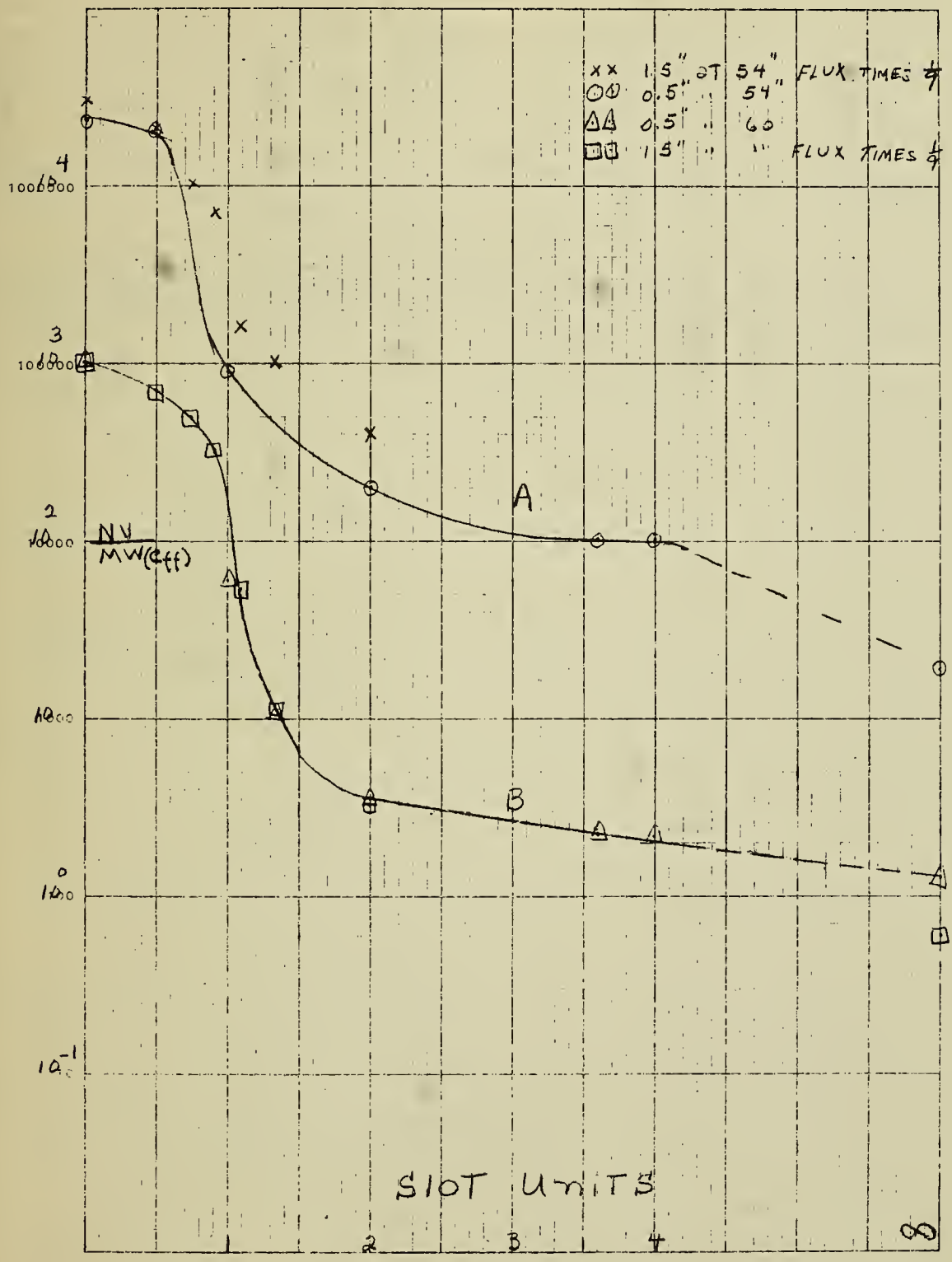

xx 1.5" 2T 54" FLUX TIMES 1/4
OO 0.5" " 54"
ΔΔ 0.5" " 60
□□ 1.5" " " FLUX TIMES 1/4
4
3
2
NV
MW(Cff)
A
B
SLOT UNITS
2
3
4

Fig. 8

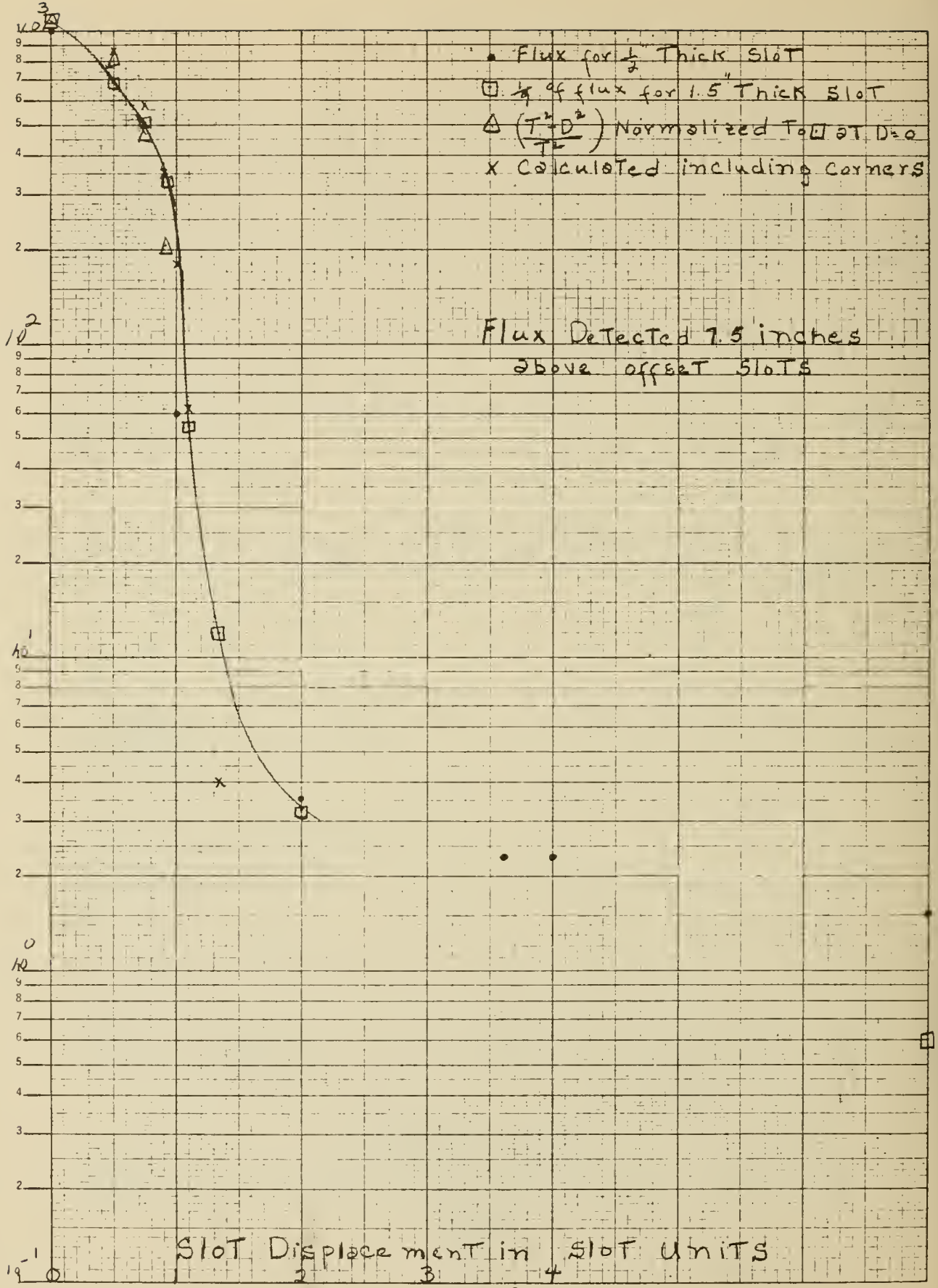

• Flux for ½ Thick Slot
□ ½ of flux for 1.5" Thick Slot
△ $\left(\frac{T^2+D^2}{T^2}\right)$ Normalized To □ at D=0
x Calculated including Corners
Flux Detected 7.5 inches
above offset Slots
Slot Displacement in Slot Units

Fig. 9

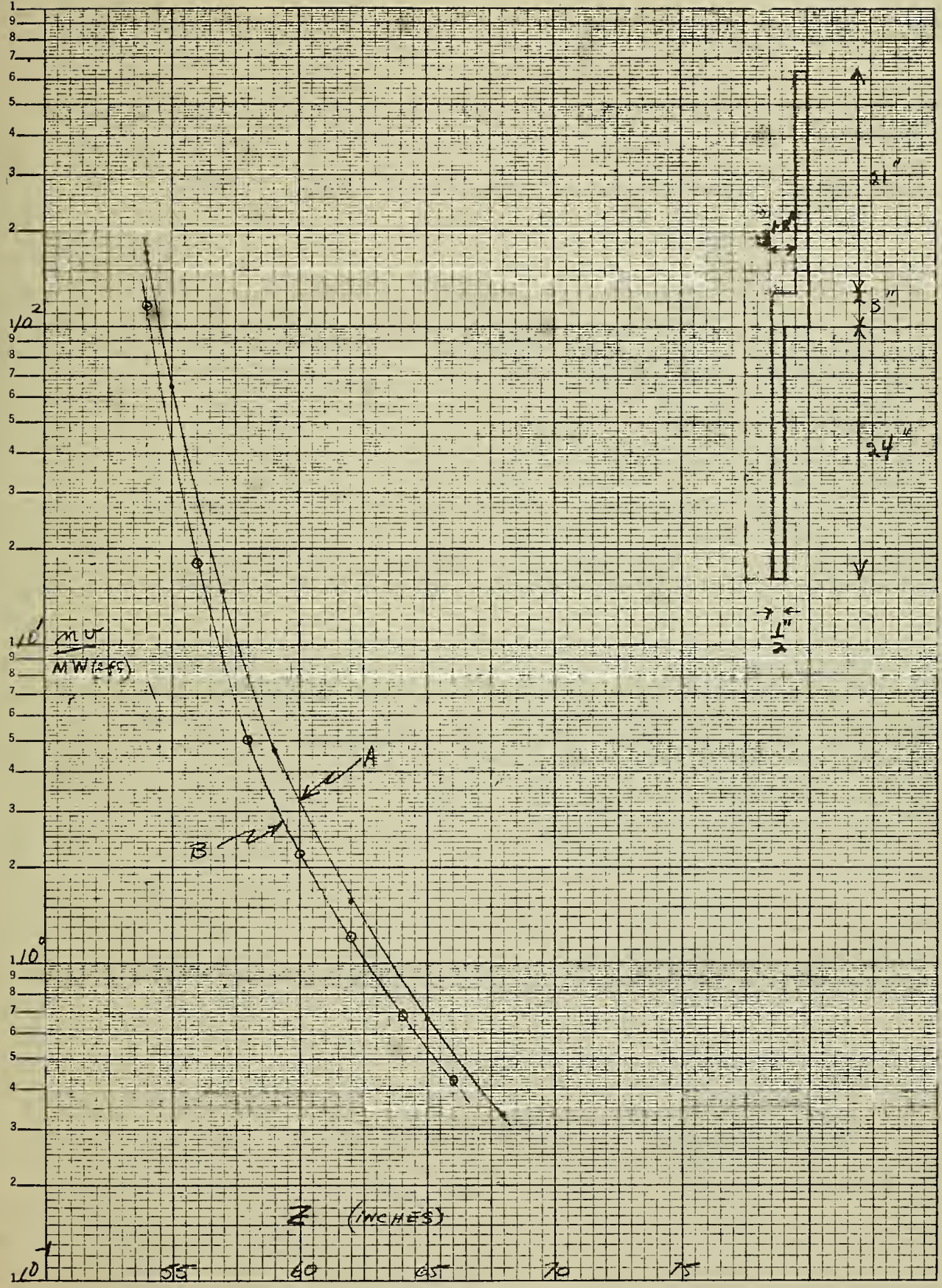


Fig. 10

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3 1262 08230 015 2